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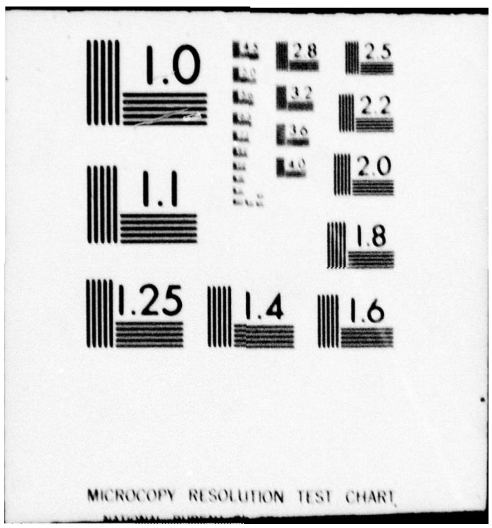
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OPTIMUM STATION DISTRIBUTION AND DETERMINATION OF HYPOCENTERS FOR SMALL SEISMOGRAPHIC NETWORKS.

by

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Design of an optimal network of seismographs around a large reservoir to locate nearby earthquakes presents a number of theoretical and practical problems.

This study discusses the aims of such networks and sets out general guidelines for network design to achieve these aims. The underlying variational problem is how to minimize and distribute the number of stations in order to achieve

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a desired level of precision in earthquake detection and hypocentral location. It is shown that a joint location method provides optimal solutions for clusters of earthquake hypocenters within a local network. A special FORTRAN program, called GHYP1 (available from the Seismographic Station, University of California) has been written to do this joint reduction with simultaneous estimation of station adjustment terms. Sensitivity analyses for representative crustal models and network patterns provide guidelines for achievable hypocentral uncertainties.

The problem of location of reservoir-associated seismicity is part of a more general inverse problem in which properties of the matrices of condition provide not only the variances and covariances of the estimates, but also indicate the sensitivity of the solution to changes in azimuths and distances of stations relative to the earthquake cluster. The mean seismic velocities in the rock layers under the reservoir can also be determined simultaneously with a trade-off between the resolution of the velocity estimates and their statistical uncertainties. Where possible, the type of seismograph and analysis system chosen should provide readings of both P and S phases for use in the matrix inversions.

Two specific cases of earthquake sequences located near reservoirs in California are analyzed in detail using GHYP1: Oroville 1975 and Briones Hills 1977. A full explanation is given of the input and output expected for this joint location method. The program is suitable for routine use.

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PREFACE

This report was prepared by Dr. B. A. Bolt, Mr. P. Okubo, and Dr. R. A. Uhrhammer, Seismographic Station, University of California, Berkeley, California, under Contract No. DACW39-76-C-0049. It is part of ongoing work at the U. S. Army Engineer Waterways Experiment Station (WES), in Civil Works Investigation Study: "Seismic Effects of Reservoir Loading and Fluid Injection," sponsored by the Office, Chief of Engineers, U. S. Army.

This study is directed by Dr. E. L. Krinitzsky, Engineering Geology and Rock Mechanics Division (EG&RMD), Geotechnical Laboratory (GL). General direction was by Mr. J. P. Sale, Chief, GL, and Dr. D. C. Banks, Chief, EG&RMD.

COL J. L. Cannon, CE, and Mr. F. R. Brown were Director and Technical Director, respectively, of WES during the period of this study.

CONTENTS

OPTIMUM STATION DISTRIBUTION AND DETERMINATION OF HYPOCENTERS FOR SMALL SEISMOGRAPHIC NETWORKS

1.0 INTRODUCTION

1.1 Background to the Problem

This study deals with the problem of the optimal design of networks of seismographic stations around a large reservoir. In recent years, the practice of placing such networks around large reservoirs to help in the mitigation of seismic risk has become widely accepted. The purpose of the sensitive seismographs is a) to determine the frequency of the local earthquakes (if any), b) to determine the location of the seismic activity and its depth, c) to determine the magnitude and some indication of the focal mechanisms of the earthquakes, and d) to allow the prediction of the fluctuations in time of the earthquake occurrence. It has been also widely recognized that in order to obtain a comparative background, it is essential to install the sensitive seismographic network in the vicinity of the dam before major construction begins.

Although this practice of making precise seismicity studies around large reservoirs has become commonplace, it is remarkable how little attention has been given to the optimum designs of the networks. The problem is a particular case of a more general one which relates to the modern practice of hypocentral location in local regions. Considerable progress has been made in this field through the use of algorithms that depend on high speed computers (Flinn, 1960; Nordquist, 1964; Turcotte, 1964).

The accuracy of the current hypocentral location algorithms now used depends upon the adequacy of the seismic travel times (or velocity variations in the crust) that are adopted. The usual situation is that the adopted values have been determined prior to the hypocentral location attempt, often

from a set of travel-time observations made at a different location. Thus, for the site in question, such as a new dam, the travel-time model used will contain errors that may result in grossly biased models, which in turn produce significantly biased locations. It has now been shown (Dewey, 1971; Douglas and Lilwall, 1972; Douglas, 1967; Bolt and Freedman, 1968) that there is a marked advantage in adjusting the preliminary locations of earthquakes simultaneously in groups, rather than one by one. The method, called joint hypocenter determination, is a special application of analysis of variance in which arrival-time measurements for many earthquakes in the region are pooled. The result is a more reliable estimate of the relative adjustments between individual hypocenters of the group. Systematic displacements of the group as a whole and in physical instabilities in the matrix inversion are minimized by the imposition of side conditions and penalty equations that restrict adjustments to small steps at each iteration.

One proven procedure to obtain realistic side constraints is to include in the simultaneous group reduction the observed times of an earthquake with a prior well-determined location. For convenience, the adopted parameters of this master earthquake may be held essentially fixed by the application of appropriate weights. The master earthquake may be, for a reservoir, a specially detonated chemical explosion with known origin time and location.

The discussion in this report makes some use of recent theoretical advances in geophysical inverse theory and indicates how in more advanced research applications inverse theory can treat the problem of optimum distribution of seismographic stations in a network and the optimum analysis of arrival times of various phases from earthquakes from within the network (Crosson, 1976). This type of description permits a better understanding

of the mathematics involved and provides measures of the resolution and precision of the calculated earthquake parameters and crustal structure. The main purposes of this report, however, are to provide practical guidelines to engineers and geologists who wish to establish a well-designed seismographic network around an engineering facility and to provide a tested and stable computer program that will allow straightforward but high quality earthquake locations to be calculated. For this reason, the more mathematical details of inverse theory in this context are not included.

1.2 Seismic Risk to Dams

A large earth or concrete dam represents a notably important type of seismic hazard evaluation problem. Not only is the dam in itself a relatively expensive project, but it is intimately involved in the whole economy through power generation, flood control, irrigation, etc. In addition, structural failure of the dam may lead to major disaster, because large populations may be exposed to sudden flooding. Major damage has occurred to earth dams from natural earthquakes; for example, the Hebgen Dam in Montana and the Lower Van Norman Dam in California. Many large dams in the United States are located in highly seismic regions close to areas that have in the past suffered from major earthquakes. It is therefore necessary to keep in mind the likelihood of future damaging shocks to these structures.

In addition to the hazard from natural earthquakes, several cases have now been documented in different countries of damaging earthquakes apparently related in some way to reservoir loading behind the dam (Bolt et al, 1977). Some of these examples have occurred in regions that have not been thought to be even moderately seismic. The clearest cases are a) Lake Kariba in Central Africa, the world's largest artificial reservoir, b) Koyna in

India, and c) Hsingfenkiang in the People's Republic of China. In these examples, the largest earthquakes reached a magnitude of 6.4. At Koyna, in addition to significant cracking of the concrete gravity dam which required a major repair and strengthening, numerous collapsed houses in the vicinity caused loss of life. Hsingfenkiang Dam, which is located in an essentially aseismic region, impounded a reservoir which, subsequent to 1959, was the site of numerous small shallow earthquakes. The principal shock of the series in 1962 had a magnitude 6.1 and produced a crack 82 meters long in the upper concrete dam structure.

The cases of induced seismicity now make it necessary to consider the risk from induced seismicity for all proposed large dams.

The idea that earthquakes might be triggered by impounding surface water is not new. In the 1870's the U.S. Corps of Engineers rejected proposals for major water storage in the Salton Sea in southern California on the grounds that such action might cause earthquakes. The first detailed evidence of such an effect came in the United States with the filling of Lake Mead behind Hoover Dam (height 142 meters), Nevada, beginning in 1935. Although it is not certain that there was no local seismicity before 1935, it is sure that after 1936 earthquakes were much more common. A network of seismographs was specially installed around Lake Mead and showed that after the largest earthquake (magnitude about 5) in 1940 the seismicity has declined. Hundreds of detected earthquakes cluster on steeply dipping faults on the east side of the lake and have focal depths of less than 8 km.

Studies of induced earthquakes from reservoir loading require a network of seismographs, adequate for the approximate location of small local earthquakes, to be in operation before the impounding of the reservoir (Bolt and

Hudson, 1975). Without such a network, it is usually impossible to establish the seismicity of the area prior to closure. Thus, the extent to which local earthquakes were a consequence of the reservoir or a part of the more general seismic pattern cannot be decided. Such a decision is essential to an evaluation of the probable location and size of future shocks, and thus is of immediate practical importance.

1.3 Monitoring of Earthquake Activity near Reservoirs

In the preclosure stage of a reservoir, where the main purpose is to establish if any local earthquakes occur usually at all, a minimum network of three to five short-period vertical component seismometers is often recommended. For such a network, a rough but adequate assessment of background earthquake frequency, location (using P and S waves), and magnitude can be made. If local earthquakes do in fact occur, the network can be expanded with additional seismometers as near as possible to the active area.

After closure, the usual advice is to operate at least a four to six station network for a period extending some years beyond the time when maximum impounding is complete. If a sequence of earthquakes does occur, then the network is usually densified. In such cases, special research is often warranted and careful theoretical considerations must be brought to bear on the optimal location of the network. Normally, the requirement is to obtain an accuracy in location of earthquake foci of about 1 km so that correlations with geological faults can be made. In the following sections, an account is given on how such a precision can be obtained with local networks of various sizes and configurations.

In practice at present, sites of the sensitive seismographs are usually selected based on practical considerations such as accessibility and

avoidance of construction. In the best cases, some individual site selection is made depending on the local geological structures. The instruments are best located on outcrops of basement rock, and in order to reduce the microseismic noise, they should be remote as can be achieved from construction activities, streams, quarries, spillways, etc. It is helpful in these respects to make field surveys of the relative background microseismic noise at the prospective sites, using a portable seismographic recorder before locations are finalized.

There are, however, more fundamental questions concerning the optimal design and layout of the network. Let us consider the following three basic problems to be solved jointly: a) What is the appropriate velocity structure or equivalently, the travel-time curves for the region in question? b) How can the specified precision of hypocentral location be obtained? and c) How can a minimum number of stations be involved? Commonly, at present, these questions are only partially treated. First, sometimes chemical explosions are fired, perhaps in connection with quarrying in the vicinity of the dam construction, to obtain observed travel-time curves that can be used in the earthquake location work. More usually, already available travel-time curves or velocities from other tectonic regions are adopted as approximations by analogy. Secondly, some general geometrical considerations are used to govern the network configuration. For example, sites of seismometers are selected to be as uniformly spread in azimuth around the reservoir as possible. The spacing between the stations is kept as equal as practical, and is usually selected so as not to exceed 30 km or be less than 5 km.

In the following sections the three joint problems above are treated in essentials. In the course of this discussion, guidelines are set down

on what kind of seismic readings should be made and with what precision in order to answer questions that arise concerning seismicity near to a reservoir. As a tool in the analysis, a simple program for a high speed computer was written for efficient and robust numerical estimation of location of the seismicity near to a reservoir. It is called GHYP1.

2.0 THE EARTHQUAKE LOCATION PROBLEM

2.1 Crustal Model and Travel Times

The simplest model for location of an earthquake focus (i.e., hypocenter) is shown in Figure 1. Four parameters need to be determined for the single focus F, namely latitude, longitude, focal depth, and origin time. The epicenter is the point on the surface directly above the focus. Stations in the region S_1, S_2, etc. receive P and S waves from the focus.* The arrival times of these waves are read from seismograms and used to develop a system of equations for the determination of the focal parameters. In Figure 1, the P and S velocities in the rocks, called V_1 and V_2, are constant, so that the ray paths from the focus to the stations are straight lines. For a rectangular set of spatial axes, the coordinates X, Y, and Z of a preliminary location relative to a local origin are related by Pythagoras' theorem by the equation

$$V(T - T_o) = (X^2 + Y^2 + Z^2)^{\frac{1}{2}} \tag{1}$$

where T_o is the origin time and T is the arrival time of the wave in question from the focus to the station. Call this case Model A.

The relation between the coordinates and the travel time is thus a non-linear one. Rather than the arrival times or travel times of the waves, the residual times (differences between the observed arrival time and expected arrival time calculated from the assumed velocity model) are used. The usual procedure is to linearize the problem on the assumption that the adjustments

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* For an elementary treatment of seismic waves and sources, see B.A. Bolt, "Earthquakes - A Primer," W.H. Freeman, 1978.

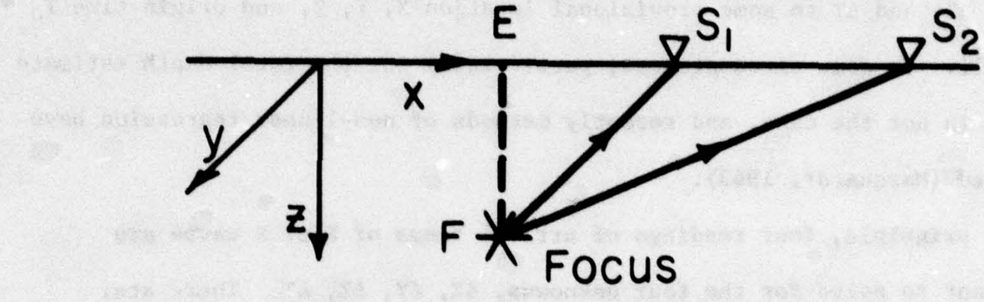
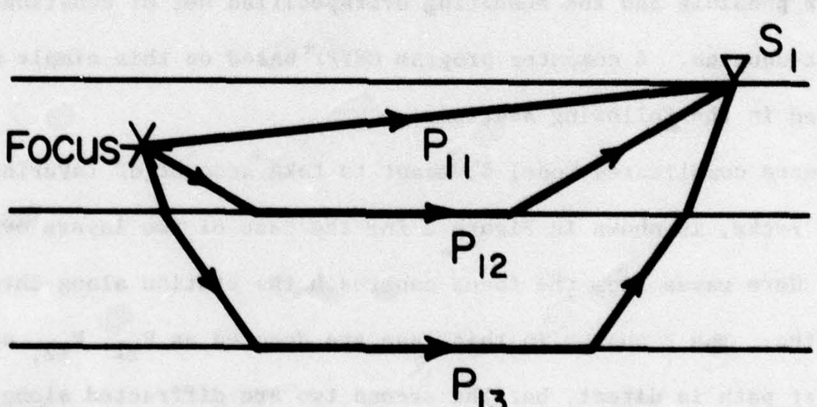


FIGURE 1



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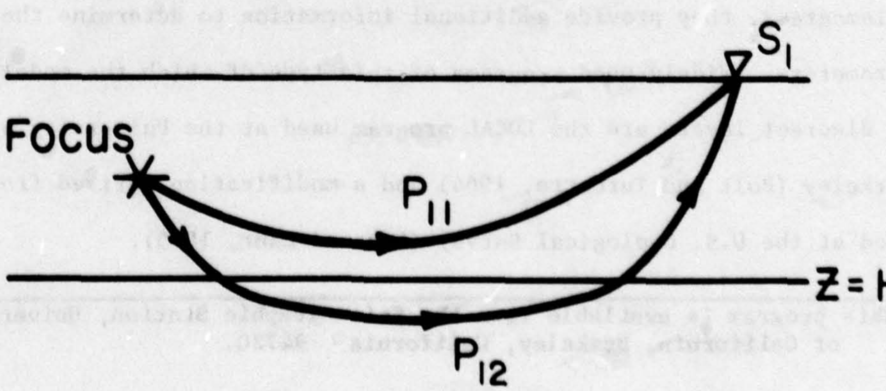


FIGURE 3

ΔX, ΔY, ΔZ, and ΔT to some provisional location X, Y, Z, and origin time T_o are small. In some circumstances, particularly for the focal depth estimate Z, this is not the case, and recently methods of non-linear regression have been used (Marquardt, 1963).

In principle, four readings of arrival times of P or S waves are sufficient to solve for the four unknowns, ΔX, ΔY, ΔZ, ΔT. There are, of course, measurement errors in these readings from seismograms and there are variations in travel time due to changes in geological structure in various directions. Therefore, more readings than unknowns are obtained whenever possible and the resulting overspecified set of equations solved by least-squares. A computer program GHYP1* based on this simple model is described in the following sections.

A more complicated Model B, meant to take account of layering in the crustal rocks, is shown in Figure 2 for the case of two layers over a half space. Here waves from the focus can reach the station along three least time paths. The P phases in this case are denoted as P_{11}, P_{12}, and P_{13}. The first path is direct, but the second two are diffracted along the boundary between the layers. Each one of these phases could arrive first on the seismogram, depending upon the layer thicknesses and the distance between the station and hypocenter. If all three phases can be read on seismograms, they provide additional information to determine the four focal parameters. Widely used programs of this type of which the model is composed of discreet layers are the LOCAL program used at the University of California, Berkeley (Bolt and Turcotte, 1964) and a modification derived from it, HYPO 71, used at the U.S. Geological Survey (Lee and Lahr, 1975).

*This program is available from the Seismographic Station, University of California, Berkeley, California 94720.

A mathematical advantage of this type of model can be seen from Figure 2. The upgoing and downgoing rays place constraints on the focal depth from above and below. Thus, if there are stations around a reservoir placed at different distances from the focus, the first arriving P_{11} and P_{13} waves (say) will give a strong estimate of focal depth.

The layered model is not as suited for study of localized seismicity around a reservoir as it is in the case of regional earthquakes, where stations range in distance from tens to hundreds of kilometers from the focus. In the case of reservoir seismicity, the distances between the focus and the station are usually less than 20 km, so that no seismic phases coming from the deeper crust and being diffracted along the discontinuity between the crust and the mantle are recorded usually on the seismograms. It is, therefore, unlikely that seismograms will show discreet wave onsets like P_{11}, P_{12}, and P_{13} which can be read.

An alternative, called Model C, is to introduce a continuous velocity increase with depth in the upper part of the crust. The rays in this case are illustrated in Figure 3. There will be continuous bending of the rays for laws which have the velocity increasing with depth. Mathematically, the effect on the solution of equation (1) is similar to the discreet layer case, because the rays may leave the focus at angles either above or below the horizontal through that point, depending on the distance of the station from the epicenter. A computer program, GHYP2, based on this model has been written and is used at the Seismographic Stations, University of California, Berkeley, but is not described further in this report.

2.2 Relative Distribution of Hypocenters and Stations

Two general theorems concerning the distribution of stations relative to hypocenters have been known for some time. The first is that, generally

speaking, stations should be evenly distributed with azimuth around the hypocenter. Thus, an epicentral error in one direction will give rise to positive residuals in that direction, and negative residuals in the opposite direction. Secondly, it is advantageous to have stations distributed over a range of distances from the epicenter of the event. The reason for this was illustrated at the end of the last section for Model B and C; at different distances the seismic waves leave the focus at different angles. Several stations at approximately the same distance and approximately the same azimuth are clearly redundant in terms of constraints. The only advantage in this case will be that the cluster of stations provides a sample of readings which will provide a mean and standard error of the measurement errors.

In order to get more quantitative rules for optimum distribution of stations relative to hypocenters, it is necessary to examine analytically and numerically the properties of the system of equations of condition developed from (1) under various laws of azimuthal and distance distribution.

Another problem arises relative to small networks, and that is that in rejecting large residuals and weighting the observations often some particular quadrant of azimuth contains only a few readings. If one of these is quite inaccurate, then the mean value for that quadrant will be grossly incorrect, and weighting will lead to nonconvergence of the solution. To handle this problem, it has been found that rather than fix the azimuthal quadrants to the cardinal points, if the quadrants are allowed to rotate so that they contain an almost equal number of stations, then optimum weighting and rejection procedures can be followed (Bolt and Turcotte, 1964).

2.3 Errors from Timing, Recording and Reading

Modern networks now consist of instrumentation for which clock errors are quite small. Sometimes a network is joined by a telemetry to a central recording station, and in this case relative errors are essentially zero. Even if each station has its own crystal clock, however, timing errors are not likely to be in excess of 0.1 second. More serious are the errors from the variations in the drum rate and in picking the onset of the phase in question. Generally, errors up to ±.3 sec are common, and when the possibility of misinterpretation of phases is included, larger errors in excess of half a second occur with a finite frequency. The problem of optimum location of earthquakes around a reservoir is therefore a statistical one, and the analysis of the problem must incorporate the statistical variations.

Two considerations arise. First, the purpose of making a joint location of foci of several earthquakes rather than calculating the position of earthquake foci separately (which has been the tradition in seismology up to the present) is to accumulate a sample of readings for a particular station. In this way the incorrect readings can be detected against the mean value of the sample. Thus, if, say, ten local earthquakes are located together, then each station of the network will have approximately ten readings of the P phase and ten readings of the S phase. These will provide a stable estimate of the mean and variance of the station measurements arising from timing, recording, and reading errors.

Secondly, the measurement errors must be treated in the program by means of a suitable weighting scheme. The computational algorithm systematically tries to improve the location estimates by successive iterative adjustments.

If the weighting scheme is too severe, it will reject residuals that appear large at the particular stage of iteration reached, but are in fact indicating that a significant shift in the hypocenter is still required. The method of weighting using a bi-weight function is recommended, and this leads to robust weighting schemes. In the program GHYP1, a Pearson type VII distribution function was used as a weighting function on the grounds that, while symmetrical, it allowed more frequent values on the flanks than the normal law.

2.4 The Simultaneous Inverse Problem

Suppose that a network of seismographs is placed around a reservoir in a planned configuration. Further, suppose that the underlying geological structure is more or less the same with minor local differences that produce slight advances and delays in the time of travel of seismic waves to each station. Thus, each station can be associated with a small time adjustment (or "correction") relative to the mean time.

If the location of the hypocenters of a sequence of earthquakes near the reservoir were known, as well as seismic velocities for the various phases in the region and time adjustments appropriate for each of the stations of the network, then it would be straightforward to calculate the travel times (and hence arrival times) of the phases to the stations. This problem is called a <u>direct problem</u>.

However, we have just the inverse of the problem stated above. We have a set of observed arrival times of seismic waves, usually P and S waves, from a sequence of earthquakes as recorded at a set of stations comprising the network. From a set of provisional hypocentral coordinates and origin times and travel times, we are required to determine improved locations of the events and improved velocities and station adjustments.

A necessary condition for solving such an <u>inverse problem</u> is that the forward problem is tractable. As we pointed out in section 2.0, the forward problem is, in fact, a non-linear problem. It can be treated as such or made more tractable by linearizing it. The latter is the approach we take here.

As argued in the last section, it is statistically advantageous not to locate earthquakes one by one, but rather accumulate the times from a number of earthquakes near the reservoir and then locate them all simultaneously in the one joint least-square computation (Douglas, 1967; Dewey, 1971; Crosson, 1976). Let us suppose that there are n earthquakes and m stations in the network. Suppose further that the number of model parameters to be adjusted (seismic velocities) is ℓ. The problem then is one of determining up to $4n+\ell+m$ unknowns. There are $n \times m$ observations, if one phase is read at the station, or $n \times 2m$ observations, if both P and S are read at one of the stations. In the latter case, for example, there may be five earthquakes recorded at six stations and a P and an S velocity correction to be estimated. Thus there would be 28 unknowns to be determined from 60 observations. Such a problem is soluble in the least squares sense.

From an analytic point of view, the problem can be thought of as one in the analysis of variance. This statistical method is well-worked out and provides a valuable theoretical framework for analysis.

3.0 MATHEMATICAL FORMULATION

3.1 The Algorithm for Simultaneous Inversion

We now set up the general problem in mathematical form along the lines explained in 2.0 for Models A and B.

Let the suffix i refer to the ith earthquake ($i = 1, \ldots, n$) and j refer to the jth station ($j = 1, \ldots, m$). Let the time adjustment special to the jth station be a_j. Consider the ith earthquake being recorded at the jth station. For simplicity, we consider only the first P wave to be measured. Equations for the additional phases (S , for example) can be easily added. Then the residual (observed minus calculated) in the measured P arrival time is r_{ij} and this is associated with a random error term ϵ_{ij}. Then we may write, correct to the first order,

$$r_{ij} + \epsilon_{ij} = \Delta t_i + L\Delta X_i + M\Delta Y_i + N\Delta Z_i + H\Delta V_l + \Delta a_j , \qquad (2)$$

where

$$L = \frac{\partial t_{ij}}{\partial X_{ij}} , \quad M = \frac{\partial t_{ij}}{\partial Y_{ij}} , \quad N = \frac{\partial t_{ij}}{\partial Z_{ij}} , \quad H = \frac{\partial t_{ij}}{\partial V_l} .$$

These partial derivatives must be calculated from the appropriate formula linking travel time with velocity and distance along a ray. In the case of the constant velocity model, the formula is equation (1).

There will be an equation like (2) for each observed phase at each station for each earthquake. This set of linear equations of condition can then be solved for the unknowns Δt_i, ΔX_i, ΔY_i, ΔZ_i, ΔV_l, and Δa_j (all i and j). The solution involves the inversion of a matrix (see below) and often has numerical problems associated with ill conditioning. The aim of network design is to remove this ill conditioning as much as possible.

The set of linear equations of condition may be written as

$$Ax = b, \tag{3}$$

where x are the unknown adjustments and b are the residuals.

Each equation can be weighted, by use of a weighting matrix W, to allow for relative uncertainties in the observations. In general, there are more observations than unknowns so that A^TA is nonsingular. Therefore,

$$x = (A^TA)^{-1} A^Tb \ . \tag{4}$$

When there are fewer observations than unknowns, the generalized least-squares inverse may be used (Bolt, 1970),

$$x = A^T(AA^T)^{-1}b \ . \tag{5}$$

In addition to the condition equations, a number of linear constraints must be imposed in general (such as requiring the sum of station adjustments to be zero). These define the constraint matrix

$$Cx = d \ . \tag{6}$$

We then solve in the computer

$$\begin{vmatrix} A^TW^TWA & C^T \\ C & o \end{vmatrix} \begin{vmatrix} x \\ \lambda \end{vmatrix} = \begin{vmatrix} A^TW^TWb \\ d \end{vmatrix} \tag{7}$$

for the hypocentral, velocity, and station adjustments x and the Lagrange multipliers λ (not used).

In addition, the allowable range of adjustments of the station terms Δa_j and P velocity ΔV_1 was controlled by augmenting the matrix equation (2) with penalty equations $\Delta a_j = 0$, $\Delta V_1 = 0$. Deviations from these values are penalized but not prevented by applying appropriate weights.

It will be clear from (3) and (2) that the matrix A will lead to ill-conditioned inverses (i.e., a nearly singular A^TA) if the equations of condition are almost parallel. This problem may be reduced by ensuring that the ratios of the coefficients L, M, N, H of (2) are as different as possible for each earthquake-station pair. That is, the stations should not be at the same distance from the reservoir. In addition, the coefficients for S waves usually differ considerably from those for P waves, so that both P and S wave onsets should be read wherever possible.

The solution is programmed to proceed by a series of steps. At each stage, the corrections are reapplied to the previous set of values of the hypocentral coordinates, origin-times, velocities, and station adjustments. This yields a new set of residuals b and a new set of coefficients A. Iterations proceed until the values of x become less than a pre-specified limit.

In the case of GHYP1, which uses (4), the weight matrix W is automatically calculated at each iteration from a Pearson Type VII law whose width is proportional to the variance of the residuals at each stage. Thus, as the solution converges, the weighting becomes more severe.

3.2 Optimization of Station Distribution

Theoretically, the properties of the matrices of condition may be examined to determine their resolving power. Usually there is partial redundancy in the constraints imposed by the measurements available. For example, two stations close together will provide two equations which are almost parallel. This ill-conditioning shows up by examining the relative magnitudes of the eigenvalues of the matrices involved.

For the present introductory summary, a numerical trial-and-error scheme has been used to illustrate the effect of varying the station locations around a small region such as a reservoir.

Consider 16 stations distributed around the reservoir, as in Figure 4, in two concentric circles, radii 5 and 10 km. Stations S_{11} and S_{18} are in the inner ring and stations S_{21} to S_{28} are in the outer ring. The epicenter of the earthquake is assumed to be at the center of the circle.

The aim of the experiment was to investigate the effect of simple changes in the arrangements of these 16 stations. Crustal Model B was used with a 1 km thick surficial layer (V_1 = 2.0 km/sec) and a 2 km thick intermediate layer (V_1 = 3.0 km/sec). The P velocity in the under layer was V_1 = 5.5 km/sec. For a focal depth of 2 km, the travel time (errorless) to the inner ring stations was 2.08 sec along a direct path (P_{21}) and the errorless time to the outer ring stations was 3.13 sec along the refracted path (P_{23} - see Figure 2). By the throw of a die these times were then varied for each station by a random station adjustment ±0.3, ±0.2, ±0.1. The resulting adjusted travel times were then used with program LOCAL to locate the epicenter of the earthquake. (Focal depth was held fixed.)

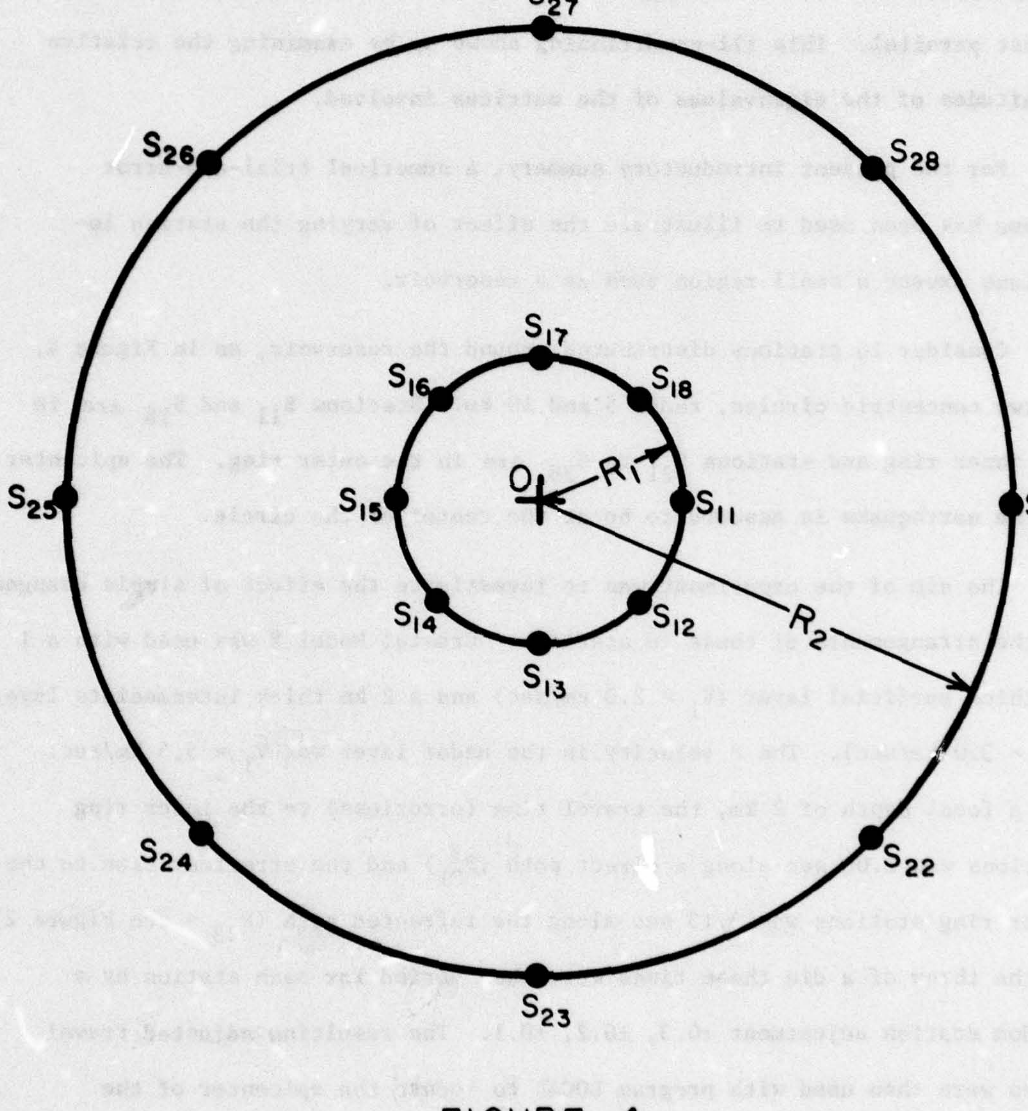

S27
S26
S28
S17
S16
S18
O
R1
S25
S15
S11
S21
S14
S12
S13
R2
S24
S22
S23

FIGURE 4

Nine cases were run with various selections of stations. For example, Case 1 had all 8 stations in the inner ring and none in the outer ring; Case 9 had S_{11}, S_{17}, S_{18}, S_{27}, and S_{28} omitted, i.e., all stations in the northeast quadrant absent.

Details of the results will not be given here, but two results illustrate the analysis.

(a) There is a dramatic loss of resolution when all stations in one quadrant were omitted (Case 9). Compared with the solution with all 16 stations present, the standard error of one observation changed from 0.31 sec to 0.37 sec and the latitude and longitude by 0.4 km.

(b) Inclusion of the second ring does not significantly alter the resolution of the epicenter when the full equispaced inner ring is in operation but drastically improves the estimation of focal depth.

We now illustrate the ideas developed in the previous sections by discussing two examples of sequences of earthquakes near reservoirs that occurred when only local networks were available for location. One is a sequence near the Oroville reservoir in central California, and the other a swarm of small earthquakes near the Briones reservoir in the hills east of San Francisco Bay. Neither network had the optimal geometrical arrangement shown in Figure 4, but where possible this should be approximated as closely as practical.

4.0 CASE STUDIES

4.1 The Oroville Sequence, August 1975

The main shock (magnitude 5.7) of the sequence (see Figure 5) occurred in the afternoon of August 1, 1975, at 1320 PDT. The region is one of low seismicity with generally a few minor earthquakes a year within 50 km of the dam site. Nevertheless, before dam construction, seismographs were installed in 1963 about a kilometer north of the dam in order to monitor the background seismicity. These instruments detected no change in the low level of earthquake occurrence within 30 km of the reservoir during filling or after the reservoir was raised to its highest elevation in 1969.

On June 28, 1975, a few small shocks were recorded southwest of the Oroville reservoir. Some additional portable seismographic stations were installed to keep better track of the position of the earthquakes. About 20 small shocks were recorded through July in the same general area, the largest of which was magnitude 4.7. After the main shock on August 1, many aftershocks followed in the subsequent weeks and many more temporary seismographs were operated in a dense local network. Locations of 51 earthquakes in the sequence are plotted in Figure 5. The main shock was located about 10 km to the south of Lake Oroville and the foreshocks and aftershocks define a region of area 10 km by 14 km to the south of the dam (Morrison et al, 1976). The focal depths ranged from 10 km to the west of this zone to near surface values to the east.

The hypocenters in Figure 5 were calculated one by one, using the routine program LOCAL, using P readings from nine stations with epicentral distances from 7 to 195 km. Only 5 stations were available at the time of the main shock at distances of 40 km or less from the epicenter. Thus, these initial

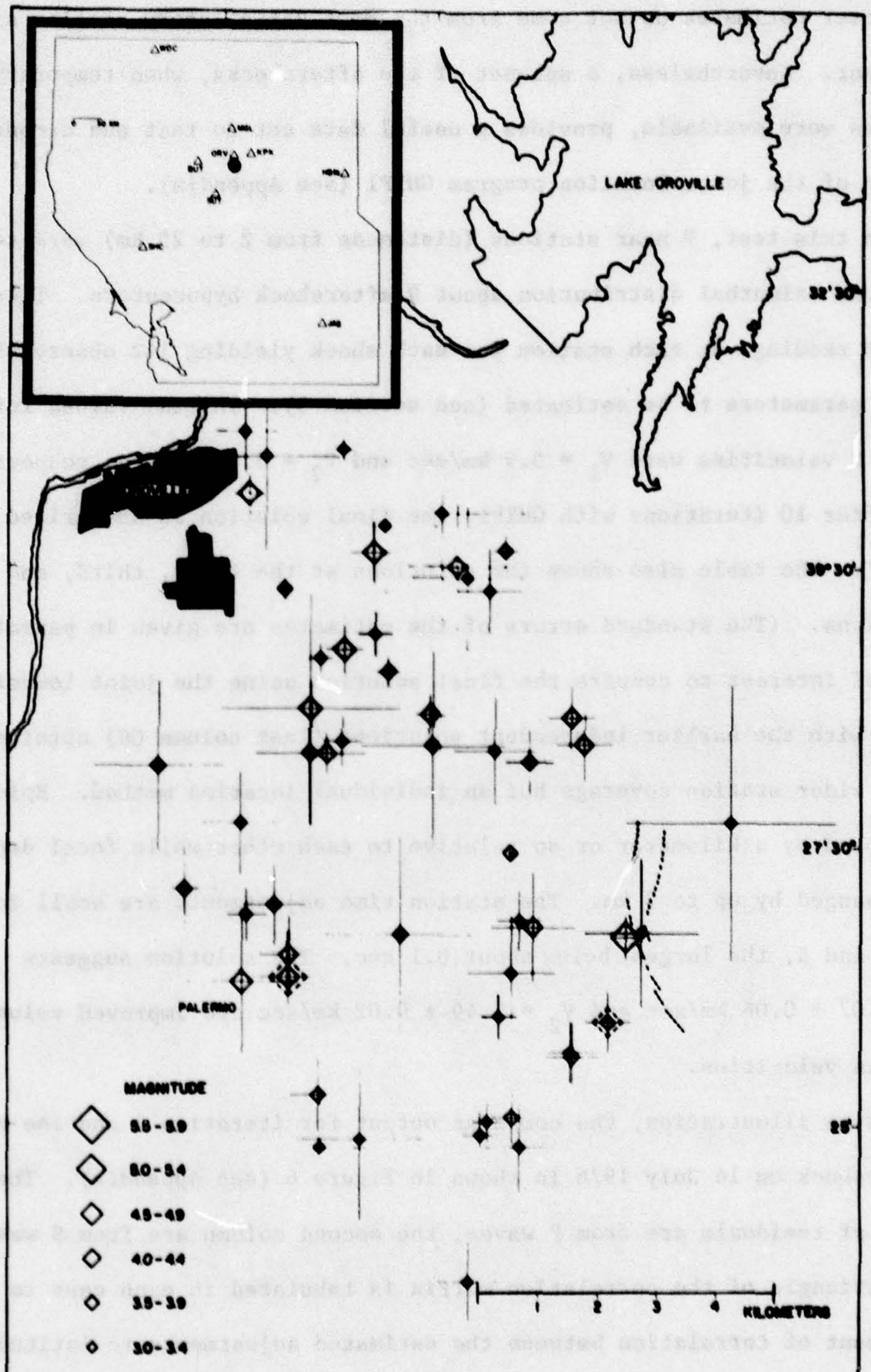


FIGURE 5

hypocenter estimates do not come from the most satisfactory station arrangement. Nevertheless, a sub-set of the aftershocks, when temporary stations were available, provides a useful data set to test and demonstrate the use of the joint location program GHYP1 (see Appendix).

In this test, 9 near stations (distances from 2 to 25 km) were selected with even azimuthal distribution about 9 aftershock hypocenters. There were P and S readings at each station for each shock yielding 162 observations and 47 parameters to be estimated (see section 3). Initial values for V_1, P, and S velocities were $V_1 = 5.9$ km/sec and $V_2 = 3.47$ km/sec, respectively.

After 10 iterations with GHYP1, the final solution is summarized in Table 1. The table also shows the solutions at the first, third, and fifth iterations. (The standard errors of the estimates are given in parentheses.) It is of interest to compare the final solution using the joint location method with the earlier independent solutions (last column GS) obtained with a wider station coverage but an individual location method. Epicenters have moved by a kilometer or so relative to each other while focal depths have changed by up to 3 km. The station time adjustments are small for both P and S, the largest being about 0.1 sec. The solution suggests $V_1 = 6.07 \pm 0.06$ km/sec and $V_2 = 3.49 \pm 0.02$ km/sec are improved values for the mean velocities.

As an illustration, the computer output for iteration 4 and the magnitude 1 aftershock on 14 July 1976 is shown in Figure 6 (see Appendix). The first column of residuals are from P waves, the second column are from S waves. The upper triangle of the correlation matrix is tabulated in each case to indicate the amount of correlation between the estimated adjustments to latitude,

FIGURE 6

OROVILLE 14 JUL 76 0301 ML = 1.0

PARAMETER	VALUE	STANDARD ERROR	CORRELATION MATRIX				PERTURBATION
ORIGIN TIME	3H 1M 57.44S	.026(SEC)	1.00	.47	-.13	-.90	.02
LATITUDE	39D 24.33M N	.08(KM)		1.00	.00	-.23	.03
LONGITUDE	121D 30.76M W	.14(KM)			1.00	.07	.02
DEPTH	6.10KM	.17(KM)				1.00	-.09

STN	DELTA	AZ	MIN	SEC	WT	RES	MIN	SEC	WT	RES
FIG	3.23	77.6	1	58.63	1.00	.01	1	59.44	1.00	.01
COX	3.86	222.9	1	58.72	.96	.02	1	59.46	.95	-.08
WYN	5.76	22.8	1	58.87	1.00	.01	1.	59.86	1.00	-.00
LON	6.59	310.8	1	59.11	.77	.10	2	.20	.72	.07
HON	8.06	162.3	1	59.11	.99	-.00	2	.31	.98	.02
LUV	11.85	.1	1	59.65	.98	-.02	2	1.24	.98	-.04
TAB	16.15	345.2	2	.33	.99	-.02	2	2.38	.98	-.01
ORV	16.54	3.7	2	.38	.98	-.03	2	2.40	.84	-.01
KPK	26.62	42.0	2	2.08	1.00	-.03	2	5.47	.72	.06

TABLE 1

GROUP LOCATION OF OROVILLE EARTHQUAKES

$\phi = 39° + N \quad \lambda = 121° + W$

PARAMETER	INITIAL SOLUTION	3RD ITERATION	5TH ITERATION	FINAL SOLUTION	GS**
0945Feb06					
OT	17.31	18.01(.052)	18.04(.026)	18.10(.028)	17.84
ϕ	28.14	29.76(.11)	29.60(.06)	29.56(.05)	29.65
λ	29.60	29.31(.23)	29.64(.14)	29.67(.12)	29.73
h	6.73	4.54(.34)	4.63(.17)	4.39(.16)	4.40
0636Feb14					
OT	26.90	27.38(.064)	27.39(.032)	27.52(.040)	27.32
ϕ	28.14	23.80(.16)	23.86(.09)	23.89(.08)	24.19
λ	29.60	29.06(.22)	28.96(.13)	28.98(.11)	28.98
h	6.73	6.51(.46)	6.47(.24)	5.83(.25)	5.66
1003Feb19					
OT	09.45	09.59(.050)	09.59(.025)	09.69(.035)	09.48
ϕ	28.14	30.32(.14)	30.22(.08)	30.16(.07)	30.31
λ	29.60	31.16(.26)	31.42(.15)	31.48(.13)	31.43
h	6.73	8.53(.28)	8.69(.14)	8.35(.15)	7.91
1214Feb19					
OT	18.38	18.65(.041)	18.65(.021)	18.77(.033)	
ϕ	28.14	24.94(.12)	24.95(.07)	24.96(.07)	
λ	29.60	29.34(.20)	29.34(.12)	29.39(.10)	
h	6.73	7.64(.25)	7.64(.13)	7.16(.15)	
0530Feb20					
OT	23.15	23.82(.088)	23.87(.042)	23.96(.040)	23.71
ϕ	28.14	23.34(.18)	23.48(.09)	23.51(.08)	23.48
λ	29.60	29.65(.34)	30.00(.16)	30.08(.13)	30.11
h	6.73	4.86(.46)	4.27(.28)	3.75(.27)	3.65
1738Feb22					
OT	34.40	35.28(.056)	35.32(.028)	35.38(.029)	35.12
ϕ	28.14	27.28(.11)	27.19(.07)	27.16(.06)	27.23
λ	29.60	30.08(.20)	30.25(.11)	30.43(.09)	30.36
h	6.73	4.05(.36)	3.78(.19)	3.43(.18)	3.57
0007Mar13					
OT	44.53	44.47(.053)	44.49(.027)	44.60(.038)	44.37
ϕ	28.14	26.35(.14)	26.38(.08)	26.38(.07)	26.62
λ	29.60	32.37(.22)	32.30(.13)	32.25(.12)	31.93
h	6.73	9.14(.29)	9.06(.15)	8.68(.16)	8.78
0301Jul14					
OT	57.04	57.43(.041)	57.44(.021)	57.55(.033)	57.30
ϕ	28.14	24.31(.11)	24.32(.07)	24.34(.07)	24.55
λ	29.60	30.75(.17)	30.78(.11)	30.80(.09)	30.70
h	6.73	6.19(.25)	6.10(.13)	5.58(.16)	5.90
0304Jul14					
OT	14.47	14.77(.050)	14.84(.025)	14.94(.033)	14.72
ϕ	28.14	24.30(.12)	24.33(.07)	24.34(.07)	24.56
λ	29.60	30.43(.22)	30.72(.12)	30.75(.10)	30.68
h	6.73	6.70(.29)	6.31(.15)	5.81(.16)	5.97

(Continued)

TABLE 1 (Concluded)

PARAMETER	INITIAL SOLUTION	3RD ITERATION	5TH ITERATION	FINAL SOLUTION	GS**
P ADJUSTMENT					
TAB	0		.025(.011)	.023(.010)	.03
COX	0		-.047(.013)	-.048(.011)	.06
LUV	0		.042(.010)	.048(.009)	.04
ORV	0		.033(.013)	.043(.011)	-.03
KPK	0		-.048(.014)	-.064(.015)	.07
FIG	0		.013(.010)	-.014(.010)	
WYN	0		.012(.009)	.014(.010)	.05
LON	0		-.055(.011)	-.059(.010)	.08
HON	0		.051(.013)	.058(.011)	-.08
S ADJUSTMENT					
TAB	0		.031(.014)	.049(.013)	-.05
COX	0		-.022(.016)	-.044(.014)	-.12
LUV	0		.016(.012)	.025(.011)	-.14
ORV	0		.140(.014)	.161(.012)	-.08
KPK	0		-.114(.019)	-.093(.017)	-.19
FIG	0		-.001(.014)	-.023(.014)	
WYN	0		.002(.012)	-.010(.013)	.05
LON	0		-.126(.015)	-.149(.013)	
HON	0		.072(.016)	.085(.015)	
VELOCITIES					
P	5.9			6.07(.057)	5.9
S	3.47			3.49(.016)	3.4

** USGS unpublished data.

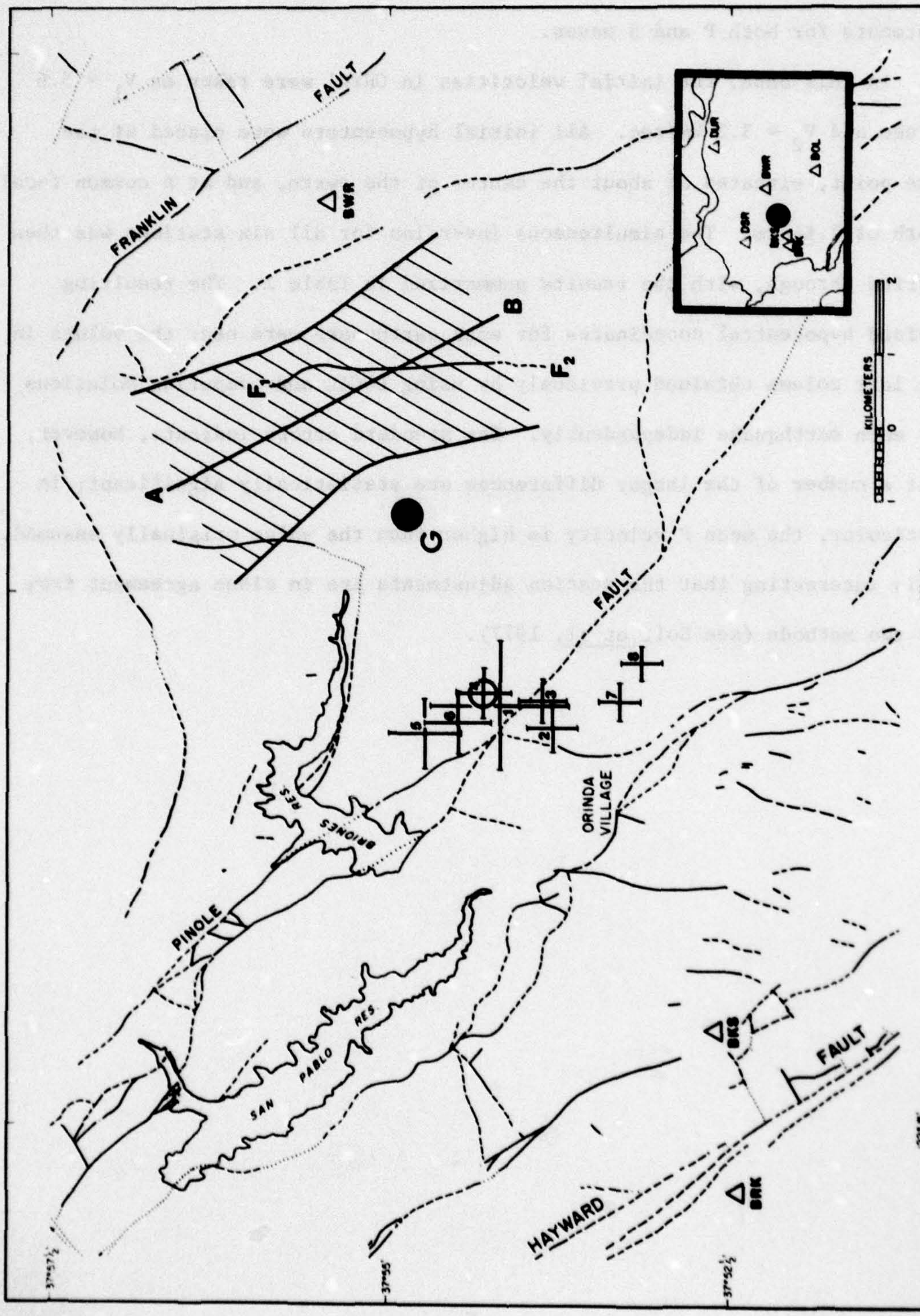
longitude, depth, etc. The relatively large 1-4 element indicates a high correlation between adjustments in origin time and focal depth, while the smaller 2-3 element indicates low correlation between adjustments in latitude and longitude. This matrix can be used to calculate uncertainty ellipses if required (see Dewey, 1971). The azimuthal distribution (epicenter to station) can be used to compare with Figure 4.

4.2 The Briones Hills Swarm, January 1977

A swarm of small to moderate shallow-focus earthquakes (Bolt et al, 1977) occurred in the vicinity of Briones Hills in Contra Costa County on the weekend of January 7 to 10, 1977 (local time). In four days, 69 earthquakes of magnitude 1.0 or greater had been recorded at the University of California station BKS situated 10 km away. The largest earthquake had magnitude 4.3. The epicenters were located near the Briones and San Pablo reservoirs and there was considerable interest in a possible link between the swarm and reservoir loading (see Figure 7).

High-quality hypocentral parameters could be estimated for eight of the earthquakes using P readings and six nearby stations (4 km < distance < 23 km) and S readings from the BKS recordings. The epicenters, calculated separately for each earthquake using Model B and the program LOCAL, are plotted in Figure 7 as crosses. Bars denote standard errors in the coordinates of the epicenters. Focal depths ranged from 7 km to 12 km. The best locations indicated that the earthquake sources were not under Briones reservoir and probably not associated with it.

This set of earthquakes provides a further suitable test of the joint location scheme discussed earlier. The P and S times for the eight earthquakes



FRANKLIN
FAULT
BWR
A
B
F_1
F_2
G
PINOLE
BRIONES
RES
SAN
PABLO
RES
ORINDA
VILLAGE
FAULT
HAYWARD
FAULT
BKS
BRK
DBR
BOL
KILOMETERS
0
2
37°57½'
37°55'
37°52½'
122°15'
122°10'
122°5'

FIGURE 7

were thus used in the program GHYP1 to obtain simultaneous estimates of location parameters, origin times, corrected velocities, and station adjustments for both P and S waves.

In this case, the initial velocities in GHYP1 were taken as $V_1 = 5.6$ km/sec and $V_2 = 3.3$ km/sec. All initial hypocenters were placed at the same point, situated at about the center of the swarm, and at a common focal depth of 7.64 km. The simultaneous inversion for all six stations was then carried through, with the results summarized in Table 2. The resulting revised hypocentral coordinates for each earthquake were near the values in the last column obtained previously by using LOCAL and computing solutions for each earthquake independently. The standard errors indicate, however, that a number of the larger differences are statistically significant; in particular, the mean P velocity is higher than the value originally assumed. It is interesting that the station adjustments are in close agreement from the two methods (see Bolt et al, 1977).

TABLE 2

GROUP LOCATION OF BRIONES HILLS EARTHQUAKES

$\phi = 37° + N \quad \lambda = 122° + W$

PARAMETER	INITIAL SOLUTION	3RD ITERATION	5TH ITERATION	FINAL SOLUTION	PAPER*
0655Jan08					
OT	50.84	50.23(.301)	50.20(.126)	50.48(.170)	50.55(.28)
ϕ	54.86	54.04(1.18)	53.98(.53)	53.64(.41)	54.19(.94)
λ	9.17	11.49(1.11)	11.55(.50)	12.11(.44)	11.09(.88)
h	7.64	13.98(1.82)	14.02(.77)	13.04(.96)	11.74(1.82)
0717Jan08					
OT	33.79	33.72(.278)	33.67(.116)	33.98(.136)	33.94(.09)
ϕ	54.86	53.70(1.08)	53.62(.48)	53.45(.37)	53.80(.32)
λ	9.17	11.57(1.02)	11.69(.46)	11.93(.37)	11.31(.30)
h	7.64	10.98(1.76)	11.21(.75)	10.03(.81)	9.33(.64)
0858Jan08					
OT	13.79	13.63(.282)	13.57(.118)	13.90(.142)	13.87(.10)
ϕ	54.86	53.77(1.08)	53.69(.49)	53.53(.37)	53.88(.35)
λ	9.17	11.32(1.01)	11.43(.46)	11.66(.32)	11.05(.32)
h	7.64	11.44(1.79)	11.69(.76)	10.46(.85)	9.65(.79)
0938Jan08					
OT	07.49	07.30(.277)	07.22(.116)	07.53(.141)	07.49(.11)
ϕ	54.86	54.26(1.04)	54.16(.47)	54.00(.35)	54.13(.37)
λ	9.17	11.14(.97)	11.31(.44)	11.56(.36)	10.97(.34)
h	7.64	10.94(1.84)	11.38(.78)	10.18(.86)	9.47(.79)
0941Jan08					
OT	02.69	02.50(.283)	02.43(.120)	02.64(.148)	02.69(.15)
ϕ	54.86	54.27(1.07)	54.06(.49)	53.59(.40)	54.74(.49)
λ	9.17	12.07(1.08)	12.30(.50)	13.24(.48)	11.35(.48)
h	7.64	11.25(1.82)	11.61(.76)	11.20(.81)	9.34(1.09)
0951Jan08					
OT	55.19	55.43(.259)	55.32(.110)	55.61(.125)	55.57(.13)
ϕ	54.86	54.54(.94)	54.39(.43)	54.27(.32)	54.50(.45)
λ	9.17	11.36(.91)	11.58(.42)	11.79(.34)	11.25(.43)
h	7.64	8.80(1.87)	9.51(.79)	8.39(.81)	7.61(1.07)
0534Jan09					
OT	16.69	16.54(.226)	16.49(.115)	16.80(.135)	16.71(.08)
ϕ	54.86	53.24(1.10)	53.15(.49)	52.97(.38)	53.31(.29)
λ	9.17	11.18(.98)	11.31(.44)	11.55(.35)	11.06(.26)
h	7.64	10.89(1.75)	11.12(.75)	9.93(.81)	9.44(.56)
0546Jan09					
OT	40.19	40.30(.262)	40.22(.110)	40.50(.124)	40.44(.08)
ϕ	54.86	53.06(1.05)	52.94(.47)	52.76(.37)	53.15(.28)
λ	9.17	10.80(.89)	10.99(.41)	11.22(.32)	10.70(.24)
h	7.64	9.38(1.77)	9.79(.45)	8.68(.78)	8.12(.57)
P ADJUSTMENT					
BKS	0		-.011(.026)	.001(.021)	-.03
BWR	0		-.257(.035)	-.293(.032)	-.19
BRK	0		.112(.034)	.170(.024)	.06
DSR	0		-.130(.038)	-.135(.027)	-.15
BOL	0		-.006(.043)	-.010(.032	-.04
DUR	0		.291(.035)	.267(.031)	.25

(Continued)

TABLE 2 (Concluded)

PARAMETER	INITIAL SOLUTION	3RD ITERATION	5TH ITERATION	FINAL SOLUTION	PAPER*
S ADJUSTMENT					
BKS	0		.127(.053)	.125(.039)	.23
VELOCITY					
P	5.6			5.98(.144)	5.6
S	3.3			3.23(.092)	3.3

* Bolt et al, 1977.

5.0 CONCLUSIONS

The following set of guidelines for the design of a limited network of seismographic stations around a reservoir or similar facility resulted from the studies outlined above.

1. Location of stations
   - a. Survey prospective sites for microseismic noise level; sites with the lowest noise levels are preferable.
   - b. Outcrops of basement rock are preferable sites to those on loose alluvium or fill.
   - c. Spacing between adjacent stations should be approximately equal and should not exceed 30 km or be less than 5 km.
   - d. The station network should be approximately centered on the facility.
   - e. Stations should be located around the facility at approximately equal intervals of azimuth.

2. Number of stations
   - a. Four stations is the minimum number required for reasonably precise location if both S and P phases can be read at all stations for most of the smaller earthquakes.
   - b. Seven stations is the recommended minimum number if an S phase can be read at only one of the stations.

3. Recommended distribution of minimum number of stations (assuming region of interest is approximately 10 km across)
   - a. Four stations: equilateral triangle 15 km on a side, with the fourth station near the center.
   - b. Seven stations: hexagon 10 km on a side with the seventh station near the center.

4. Other criteria

a. Onset times of P and S waves should be measured to an accuracy of at least 0.05 seconds and preferably to 0.02 seconds.

b. Station locations should be known to within 10 meters.

c. Magnification of each station should be set to a level where the excursions of the trace on the recording device due to the background microseisms are about 0.5 to 1% of full scale.

When P and S measurements come from a network designed using the above guidelines, the group hypocenter location program GHYP1 results in formal estimates of standard errors of about 0.2 km for epicenter location and 0.3 km for depth (or better). These uncertainties are sufficiently small to permit correlation with surface geological features.

6.0 ACKNOWLEDGMENTS

Mr. D. Michniuk helped with computations in Section 3.2 and Mr. A. Lindh kindly provided access to USGS Oroville measurements. The work was supported by a grant from the Corps of Engineers, DACW39-76-C-0049.

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APPENDIX A: GHYP1 USERS GUIDE

Program GHYP1 is designed to locate local earthquake sources by groups, rather than individually, using a small array (less than 40 km, say) of seismographic stations and a half-space velocity model (see Figure 1). GHYP1 can accept data for up to 10 earthquakes recorded by up to 10 stations and each station can have a P and/or an S observation for each earthquake.

The program simultaneously estimates:

1. hypocentral parameters,
2. station adjustments (to be added to calculated times), and
3. P and S propagation velocities.

The estimation is made by first-order adjustments to a starting solution that is automatically provided; velocities must be specified.

A FORTRAN listing and card deck of the program GHYP1 are available at the U.S. Army Engineer Waterways Experiment Station and at the Seismographic Station, University of California, Berkeley.

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Data Input Format

1. Read VP,VS,SMAX,NIT1,NIT2,NITMAX,(JS(I),I=1,5)

   Format (3F10.2,8I5)

   where:

   VP = initial P wave velocity (km/sec) (5.6, say)

   VS = initial S wave velocity (km/sec) (3.3, say)

   SMAX = maximum step size (used to determine if solution for system of equations has converged). Suggest SMAX ~ VP*ΔT where ΔT is resolution in reading onset times. (SMAX ~ 5.6x.02 ~ .1, say)

   NIT1 = Number of iterations solving for hypocentral parameters only. (usually = 2 or 3)

   NIT2 = Number of iterations solving for hypocentral parameters and station adjustments. (usually = 1, 2, or 3)

   NITMAX = Maximum number of iterations. Number of iterations solving for hypocentral parameters, station adjustments, and velocity model = NITMAX-NIT1-NIT2. (NITMAX ~ 7 to 12, say)

   JS(1) to JS(5) are printing sense switches.

   JS(1)=0: print station location and phase data.

   JS(2)=1: print station coordinates and parameters used in setting up the size of the equation of condition matrix.

   JS(3)=1: print equations of condition.

   JS(4)=1: print the variables involved in solving the system of normal equations.

   JS(5)=1: print perturbation of parameters

   <u>Note:</u> JS(2) to JS(5) apply to each iteration.

2. Read in station data (up to 10 stations)

Read SNAME(I),SLATD(I),SLATM(I),SLONGD(I),SLONGM(I)

Format (A3,1X,F2.0,F5.2,1X,F3.0,F5.2)

where:

SNAME(I) = station code (up to 3 characters)

SLATD(I) = station latitude (degrees)

SLATM(I) = station latitude (minutes)

SLONGD(I) = station longitude (degrees)

SLONGM(I) = station longitude (minutes)

Note: latitude is assumed to be North and longitude to be West.

Repeat for each station and after the last station place and end-of-record (EOR) in the card deck.

3. Read in phase onset time data (up to 10 earthquakes).

a. Read (ID(I),I=1,8) ~ arbitrary title to identify the event.

Format (8A10)

b. Read STN(I),PH(I),PM(I),PS(I),SH(I),SM(I),SS(I)

Format (A3,1X,2F2.0,F5.2,1X,2F2.0,F5.2)

where:

STN(I) = station code

PH,PM,PS = P wave onset time in hours, minutes, and seconds (to .01 sec).

SH,SM,SS = S wave onset time in hours, minutes, and seconds (to .01 sec)

Repeat step b for each station observations.

c. EOR

Repeat steps a, b, and c for each event.

4. EOR to indicate end of input data.

Computational Method

GHYP1 uses constrained linear least-squares with penalty functions to solve a system of equations and the techniques of analysis of variance are used to estimate the standard errors of, and correlations between, the unknown parameters from the standard error of the residuals. The observations are weighted by their residuals using a Pearson's Type VII distribution.

Constraint equations are used to constrain the sum of the P station adjustments and, if applicable, the S station adjustments, to be zero. These constraints are necessary to avoid a singular system of equations due to unity correlation between the station adjustments and the origin times of the earthquakes.

Penalty functions are used to restrain the perturbations in the station adjustments, the velocities, and the velocity ratio to be small (less than 0.1, say) in order that the solution to the system of normal equations remains stable.

The initial location for each epicenter is the geometrical center of the array and the depth is 0.7 of the average radius to the stations. The initial origin time depends upon the initial velocity model.

GHYP1 Output

The program prints out, for each iteration where applicable:

1. The hypocenter for each earthquake, including

   a. standard errors of parameters

   b. correlation matrix (used to construct error ellipsoid (uses left-hand coordinate system))

   c. perturbation of each parameter from previous iteration.

2. Station data for each earthquake, including:

   a. delta (km)

   b. azimuth (epicenter to station)

   c. P onset time, weight, and residual

   d. S onset time, weight, and residual.

3. Station adjustments and standard errors for P and S.

4. P and/or S velocities and standard errors.

Included in the output for each iteration is an estimate of the number of significant figures in the solution, and the standard error of the solution.

In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Bolt, Bruce A

Optimum station distribution and determination of hypocenters for small seismographic networks / by Bruce A. Bolt, Paul Okubo, Robert A. Uhrhammer, Seismographic Station, University of California, Berkeley, California. Vicksburg, Miss. : U. S. Waterways Experiment Station ; Springfield, Va. : available from National Technical Information Service, 1978.

43 p. : ill. ; 27 cm. (Miscellaneous paper - U. S. Army Engineer Waterways Experiment Station ; S-78-9)

Prepared for Office, Chief of Engineers, U. S. Army, Washington, D. C., under Contract No. DACW39-76-C-0049.

References: p. 36-37.

1. Earthquakes. 2. GHYP1 (Computer program). 3. Hypocenters. 4. Reservoirs. 5. Seismic detection. 6. Seismographs. 7. Seismological stations. I. Okubo, Paul, joint author. II. Uhrhammer, Robert A., joint author. III. California. University. Seismographic Station. IV. United States. Army. Corps of Engineers. V: Series: United States. Waterways Experiment Station, Vicksburg, Miss. Miscellaneous paper ; S-78-9.

TA7.W34m no.S-78-9